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## **Automated romberg testing in patients with benign paroxysmal positional vertigo and healthy subjects**

Adelsberger, Rolf ; Valko, Yulia ; Straumann, Dominik ; Troester, Gerhard

**Abstract:** Objective: Benign paroxysmal positional vertigo (BPPV) is the most common cause of dizziness. The underlying pathomechanism responsible for the recurrent vertigo attacks has been elucidated in detail, and highly effective treatment strategies (liberation maneuvers) have been developed. However, many BPPV patients complain about problems of balance especially following liberation maneuvers. Aim: To objectively demonstrate differences in balance performance in BPPV patients compared to healthy subjects both prior and after BPPV liberation maneuvers. Methods: Seven patients with BPPV of the posterior semicircular canal and 9 healthy subjects participated. To assess balance while standing, we analyzed the location and temporal stability of the center of pressure recorded by pressure-sensitive electronic soles during Romberg testing (on stable ground and on foam) and tandem stand. To assess regularity of gait, we analyzed the step frequency during walking of 50m. All tests were performed prior and after liberation maneuvers in both groups. Results: Healthy subjects and patients differ significantly in their balance performance and use different stabilization strategies both prior and after liberation maneuvers. Both Romberg tests indicated poorer balance in BPPV patients (mean COP shifted towards toes), especially in the post-treatment tests, while tandem stand appeared unaltered. We did not observe differences in escorted (by an experimenter) walking regularities between patients and healthy subjects and between pre- and post-maneuver testing. Conclusion and significance: Our findings confirm the typical clinical observation of a further post-treatment deterioration of already impaired postural performance in BPPV patients. While the etiology and the time course of this peculiar problem warrants further studies, the treating physician should be familiar with this transient side effect of therapeutic maneuvers to provide adequate counseling of patients. Finally, we successfully demonstrated the pressure-sensitive electronic soles as a new and potentially useful tool for both clinical and research purposes.

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# Automated Romberg Testing in Patients With Benign Paroxysmal Positional Vertigo and Healthy Subjects

Rolf Adelsberger, Yulia Valko, Dominik Straumann and Gerhard Tröster

**Abstract—Objective:** Benign paroxysmal positional vertigo (BPPV) is the most common cause of dizziness. The underlying pathomechanism responsible for the recurrent vertigo attacks has been elucidated in detail, and highly effective treatment strategies (liberation maneuvers) have been developed. However, many BPPV patients complain about problems of balance especially following liberation maneuvers.

**Aim:** To objectively demonstrate differences in balance performance in BPPV patients compared to healthy subjects both prior and after BPPV liberation maneuvers.

**Methods:** Seven patients with BPPV of the posterior semicircular canal and 9 healthy subjects participated. To assess balance while standing, we analyzed the location and temporal stability of the center of pressure recorded by pressure-sensitive electronic soles during Romberg testing (on stable ground and on foam) and tandem stand. To assess regularity of gait, we analyzed the step frequency during walking of 50m. All tests were performed prior and after liberation maneuvers in both groups.

**Results:** Healthy subjects and patients differ significantly in their balance performance and use different stabilization strategies both prior and after liberation maneuvers. Both Romberg tests indicated poorer balance in BPPV patients (mean COP shifted towards toes), especially in the post-treatment tests, while tandem stand appeared unaltered. We did not observe differences in escorted (by an experimenter) walking regularities between patients and healthy subjects and between pre- and post-maneuver testing.

**Conclusion and significance:** Our findings confirm the typical clinical observation of a further post-treatment deterioration of already impaired postural performance in BPPV patients. While the etiology and the time course of this peculiar problem warrants further studies, the treating physician should be familiar with this transient side effect of therapeutic maneuvers to provide adequate counseling of patients. Finally, we successfully demonstrated the pressure-sensitive electronic soles as a new and potentially useful tool for both clinical and research purposes.

**Index Terms—**BPPV, Bipedal Performance, Balance, Center of Pressure, COP, Embedded, Sensors

## I. INTRODUCTION

Copyright (c) 2013 IEEE. Personal use of this material is permitted. However, permission to use this material for any other purposes must be obtained from the IEEE by sending an email to [pubs-permissions@ieee.org](mailto:pubs-permissions@ieee.org). R. Adelsberger and G. Tröster are with ETH Zurich. Y. Valko and D. Straumann are with the University Hospital, Zurich. Manuscript received June 25, 2014; accepted August 24, 2014

THE probability that a person experiences benign paroxysmal positional vertigo (BPPV) at least once during his lifetime is 2.4% [1]. BPPV is by far the most common neurological disorder [2], [3], [4], [5], [6], [7]. Whilst the signs and symptoms of BPPV (vertigo, disorientation, autonomic disturbances) can be wearing, the prognosis is excellent: 80%–90% of the patients do not show signs of BPPV after the first treatment, close to 100% are free of symptoms after the third. Often, BPPV also resolves spontaneously [8]. BPPV is caused by detached calcium carbonate crystals that float freely in the endolymph of the vestibular labyrinth. Normally, these crystals are attached to the otolithic membrane where they enable the sensing of linear acceleration including gravity. If, on the affected side the free-floating crystals happen to enter one or more of the three semicircular canals, this so-called canalolithiasis causes BPPV whenever patients re-orient their heads relative to gravity. Since the specific weight of the crystals exceeds the specific weight of the endolymph, the crystals always sediment to the lowest point of the affected semicircular canal, thereby causing a temporary deflection of its cupula. This effect, in turn, leads to a transient change of the firing rate in the respective vestibular neurons and consequently to nystagmus and vertigo [9]. Canalolithiasis, and therefore BPPV, is best diagnosed by the Hallpike maneuver (for the posterior semicircular canals) [10] or the supine roll maneuver (for the lateral semicircular canals) [11], [12]. The direction of the positional nystagmus elicited by these maneuvers (Hallpike: geotropic vertical-torsional positional nystagmus; supine roll: geotropic or apogeotropic horizontal positional nystagmus) allows determining which of the three semicircular canals is affected by canalolithiasis on either side. Apart from positional vertigo, patients often report various degrees of unsteadiness during standing and walking, which is probably due to the abnormal vestibular signals from the affected semicircular canals. Canalolithiasis is a benign condition, as it can be treated by so-called liberation maneuvers that have a very high success rate (up to 80–90% of a single maneuver [13]). Rarely, patients need repetitive maneuvers, which are usually performed at intervals of a few days [14]. The liberation maneuvers for the most common form of BPPV, i.e. the canalolithiasis of a posterior semicircular canal, are the Epley [15] (see Figure 3) and the Semont [16] maneuvers. After liberation maneuvers, despite their effectiveness, patients commonly experience a transient unsteadiness [17]. This feeling of decreased stability while standing and walking may last hours, sometimes up to several days. To the best

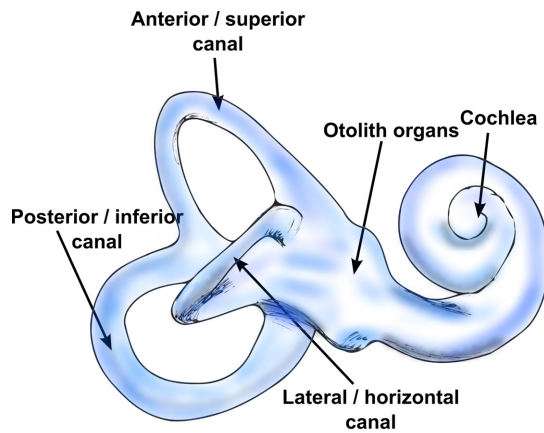


Fig. 1. Illustration of the inner ear.

of our knowledge, it has never been assessed, whether this post-liberation-maneuver symptom reflects genuine imbalance. The aim of this study, therefore, was to objectively quantify postural balance immediately after liberation maneuvers and compare it to measurements performed before the maneuvers. We asked the following questions:

- 1) Are bipedal performances of BPPV patients significantly impaired as a result of canalolithiasis?
- 2) Do canalolith liberation maneuvers lead to measurable deteriorations of bipedal performances of BPPV patients? We hypothesized that in patients with BPPV, liberation maneuvers would move the crystals out of the affected canal back to the utricle where they would sediment upon the utricular macula and potentially disturb gravity perception and hence postural stability [17].
- 3) Do liberation maneuvers also lead to a transient deterioration of bipedal performances in healthy human subjects and, if present, are they different from those in BPPV patients?

We formulate these questions in three hypotheses:

- H1:** Bipedal performance in BPPV patients are statistically significantly different to performance in healthy subjects.
- H2:** Bipedal performance deteriorates in BPPV patients as a result to canalolith liberation maneuvers.
- H3:** Liberation maneuvers do not have a statistically significant effect on bipedal performance in healthy subjects.

Assessing bipedal performance, i.e. parameters of standing and walking, is not a trivial task. Studies so far used force sensitive platforms (by, e.g. Kistler, AMTI etc.), treadmills equipped with a force sensitive belt (e.g. Zebris), force sensitive surfaces (by, e.g. GaitRite) or optical motion tracking (e.g. Vicon). Generally, these systems provide good temporal and spatial resolution; a major drawback, however, is their stationary setup. These systems have a limited acquisition area (e.g. GaitRite, Vicon), need to be installed in a dedicated location

(e.g. Vicon, Zebris), or require special gear worn by subjects (e.g. optical markers, Vicon). In contrast to an estimation performed by other systems, we used a self-developed system that directly measures the force applied to the subjects' feet soles with more than 1200 pressure-sensitive points. For this study, the system was integrated in gymnastic shoes of different sizes. A smart phone was used as a remote controller via a wireless connection. Direct streaming to the smart-phone was possible, but the data were also stored on a local memory card for later download and offline computational analysis. The technology and analysis elaborated in this work can deliver the required information on the effects of treatments affecting bipedal performance.

## II. METHODS AND MATERIAL

The Romberg test and its variants, which reflect postural control, are most commonly assessed by a medical expert who scores different aspects of the subject's performance. While some parameters are measurable, e.g. time, others allow a qualitative appraisal only. Thus, the *degree of imbalance* is very difficult to assess by visual inspection and requires an experienced expert.

Several systems provide objective measures of different features of gait. The GaitRite system is a pressure sensitive carpet. Depending on the model, the GaitRite system can be up to 10m long. Subjects are required to walk over the carpet and the system measures and calculates balance distribution, stance width, speed etc. The Zebris system consists of a treadmill with a pressure-sensitive surface. While this system is not limited in length, the locomotion in place influences the walking style of subjects [18].

### A. Assessments

The study was approved by the local ethical review committee. All subjects were given a small brochure with relevant information on BPPV, the study procedure and sensor setup, possible risks, privacy and the freedom to withdraw from participating in the study at any time without consequences. If subjects agreed to participate, they were asked to sign the corresponding consent form.

### B. Subjects

Testing was performed on the ward of the Interdisciplinary Center for Vertigo and Balance Disorders of University Hospital Zurich. Participants were selected consecutively from the group of scheduled outpatients seen by a neurologist, whenever the patients gave a typical history of BPPV due to canalolithiasis. If, in the course of the protocol, the patients did not show typical positional nystagmus following the provocation maneuvers at the bedside, they were excluded from the analysis. The data acquisition protocol did not interfere

with diagnostic and therapeutic procedures and the clinical appointment was only slightly prolonged. Healthy control subjects were recruited among the co-workers of the authors. There was no positional nystagmus detected in any of the control subjects.

### C. Tools

The recording system consisted of two parts: an inertial measurement unit (IMU) and a force-sensitive plastic foil with more than 1200 force-sensitive resistors (see Figure 2). The IMU recorded acceleration, rotation rates and magnetic field readings, each in 3 dimensions. The force data were structured in a 2-dimensional matrix: X-coordinates (1-20) represented the transversal dimension (inner side to outer side of the feet), Y-coordinates represented the longitudinal dimension (from heel to toes). The system was compared in related work to state-of-the-art systems, e.g. the Zebris Rehawalk system (see [19]). A sensing element covered  $5 \times 5 \text{ mm}^2$ , thus an increment of 1 in one dimension represented a physical shift of 5mm in the same direction. The foil matched the shape of a foot and could be adapted with a pair of scissors, e.g., to match any shoe size. We prepared three different size pairs: EU sizes 37, 42 and 46. The sensor foils were then glued into gymnastic shoes using double-sided adhesive tape. Gymnastic shoes were preferred over the patients' personal shoes due to their simplicity (no artificial heel rise or bendings on the sole) and the tight fitting to the feet.

During all tests, the system recorded inertial measurement unit (IMU) data of both feet, e.g. acceleration, rotation rates and magnetic field values at 128Hz. Concurrently, the sensors sampled the force distribution beneath the subjects' feet. All data were stored on the SD cards of the sensors for off-line analysis.

The participants were asked to perform a set of four standardized tests, including variations of the Romberg test [20], before and after therapy that consisted of the liberation maneuver. Participants were first asked to stand still with their eyes closed and with their feet put side by side for 20 seconds (test **R1**). The second test was similar: participants had to repeat task 1 while standing on a foam mat, as shown in Figure 7a (**R2**). The third test consisted of tandem stance on the floor with eyes closed (**T**). Finally, all participants were asked to walk straight 50 meters at their personal pace along the corridor (**W**). In-between two blocks of the four tests, the liberation maneuver was applied. With the Epley maneuver (see Figure 3) free floating crystals were repositioned into the utricle. In the course of the Epley maneuver, the head was rotated from the Dix-Hallpike position, in which vertigo and nystagmus occurred (Figure 3b), by 90 degrees to the Dix-Hallpike position on the other side (Figure 3c) and then by another 90 degrees in the same direction (Figure 3e). To enable the latter head rotation, the body was rolled to the side position. Finally, the patient was brought up to the sitting position (Figure 3f). In all four positions of the Epley

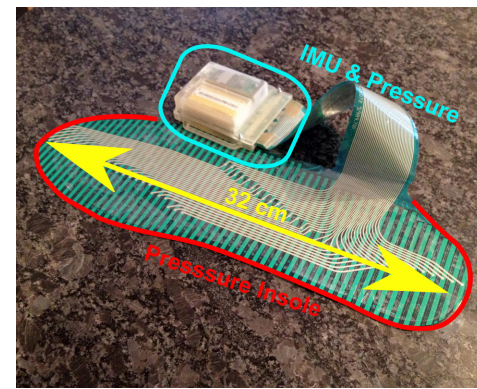


Fig. 2. Sensor system: the plantar-pressure sensor foil at maximal size and the box containing the electronics.

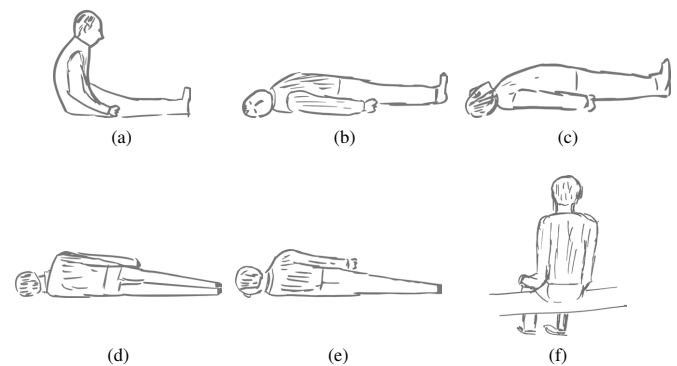


Fig. 3. Stages of the Epley maneuver to liberate the right posterior semicircular canal.

maneuver, the head was kept still for at least 30 seconds or as long as the nystagmus lasted.

### D. Protocols

All participants were first required to read the information sheet describing the condition of having BPPV. This document summarized in lay language the causes and symptoms of BPPV, and the therapeutic procedure. Additionally, the document also described the sensor technology and to what extend the subjects' participation in the study would impact the clinical appointment, e.g. the slightly longer duration. Participants were informed that the Epley maneuver does not have any persistent or major side effects.

We asked the participants about their shoe size and provided them with the best-fitting pair of gymnastic shoes. The first experimental block consisted of the four tests described in a previous section while data were recorded by the sensor system. The tests *Romberg* (**R1**), *Romberg on foam* (**R2**), *tandem stance* (**T**) and *walking* lasted 3 minutes on average. Therapeutic maneuvers were performed immediately thereafter. BPPV patients were treated with the Epley maneuver on the side of the posterior canalolithiasis. Healthy subjects were also exposed to Epley maneuvers, first on the left, then on the right side. The maneuvers were always performed by



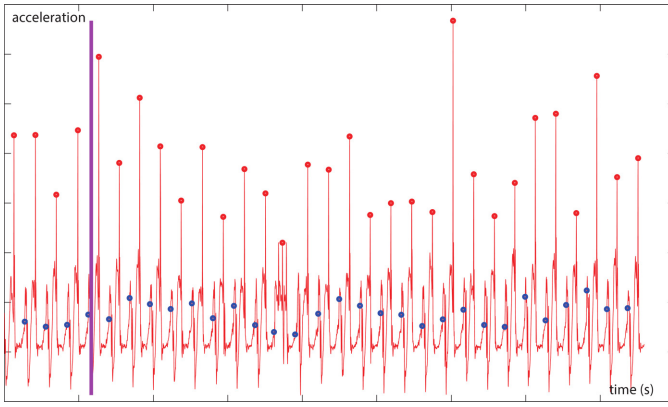


Fig. 5. IMU data: accelerometer magnitude in red. Red circles are impact points, blue circles denote toe-off events. The purple bar marks the frame visualized in Figure 6c.

the same neurologist. In patients, the Dix-Hallpike provocation maneuver was repeated after the Epley maneuver to detect a possible persistence of the positional nystagmus. If positional nystagmus was still present, the Epley maneuver was repeated until subsequent Dix-Hallpike maneuvers revealed absence of positional nystagmus.

After successful Epley maneuvers, the three balance tests and the walking test were repeated. Then, the sensor system was switched off and the participants took the gymnastic shoes off.

### E. Analysis

Analysis was based on both the pressure data and the inertial data.

Firstly, intervals in the data stream were appropriately labeled and extracted for each subject, i.e. the tests *Romberg*, *Romberg on foam*, *tandem*, and *walking* before and after the liberation maneuvers. In Figure 4, IMU acceleration data are visualized for the three spatial dimensions. Since a subject was required to stand still during Romberg testing (first three tests), the acceleration data did not modulate substantially. Subjects needed to take some steps from ground to the foam mat etc. Thus, these transitions were easily detectable in the data stream. We manually selected the intervals for the individual tests and ensured that only relevant periods were included and no data of a subject moving his/her feet (e.g. in the transition phases).

To address the issue of different shoe sizes of tested subjects, we normalized all data sets to the data size of  $20 \times 60$  by linear interpolation. We calculated center-of-pressure (COP) coordinates for all four tests. Additionally, for the walking test, the system automatically extracted the timestamps when the feet made contact to the ground. Two consecutive timestamps defined a step cycle, i.e. stride-to-stride. We did not consider higher-level features such as stance, swing, toe-off and other phases of gait.

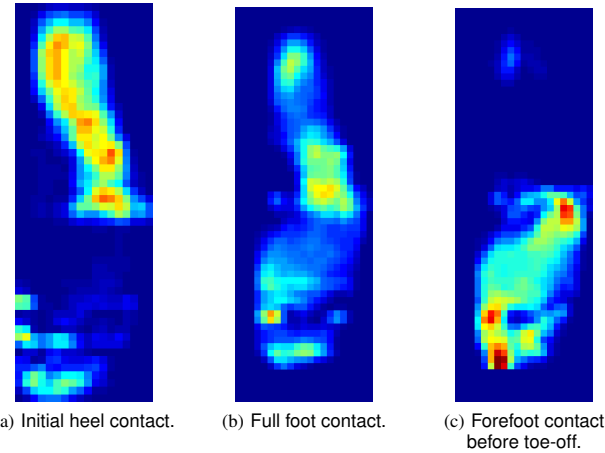


Fig. 6. Different stance phases of the force data. Feet are oriented top-down: heels are in the top, toes at the lower part of the images.

In Figure 6, different frames during a stance phase are shown for a typical subject. Contact to ground usually started at the heel (Figure 6a) and continued until the entire foot touched the ground (Figure 6b). Later, the heel lifted off the floor (Figure 6c), until, finally, the entire foot was lifted off the floor. We did not impose a specific orientation of the IMU sensor relative to a subject's shin: it was attached in an arbitrary angle and therefore sensed acceleration along every dimension with an unknown percentage of the total acceleration. We therefore calculated accelerometer magnitude and used this signal for step detection (red curve in Figure 5). The peaks of magnitude marked with red circles are impact points, i.e. the time-stamps when a foot made contact to the ground. Blue circles are toe-off events, i.e. the event when the foot left the ground entirely and thus, the signal from the pressure sensor became irrelevant. COP data and gait data were further analyzed with a moving-window approach. We used 300ms windows with 50% overlap. Similar approaches used smaller window sizes (170ms) which resulted in false positives on our data [21]. A 300ms wide window resulted in no false positives. In every window, we computed the parameters listed in Table I.

We performed repeated two-factor analysis of variance, ANOVA ( $\alpha = 0.05$ , factors = [Group{BPPV,Control}], Condition{pre-,post-therapy}), to test our hypotheses and to derive the relevant parameters. Regarding the analysis for hypothesis **H2**, we trained and tested the supervised classifiers *Support Vector Machines (SVM)*, *k-Nearest Neighbors (kNN)*, *Naïve Bayes (NB)*, as well as the unsupervised classifiers *k-Means (kM)* and *Gaussian Mixture Model (GMM)*. The classifiers were trained and evaluated; classification performances were evaluated with 10-fold cross-validation.

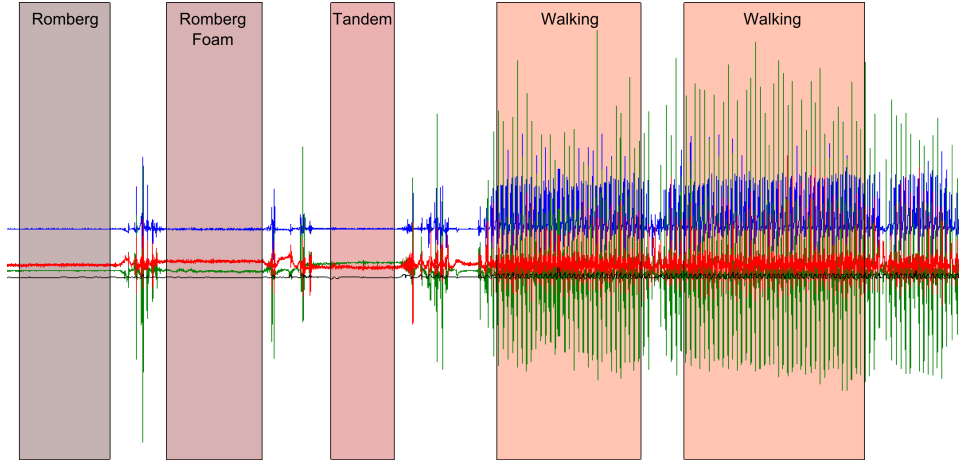


Fig. 4. Labeling data samples. Horizontal axis denotes time (i.e. sample index), vertical axis is sensed acceleration.

TABLE I  
DESCRIPTION OF THE FEATURES;  $N$  IS THE NUMBER OF ELEMENTS.  $P(k)$  IS THE PROBABILITY FOR  $k$ .

Feature	Symbol	Formula
$mean(x)$	$\mu(x)$	$1/N \cdot \sum_{i=1}^N x_i$
$variance(x)$	$\nu(x)$	$\mu((x - \mu(x))^2)$
$median(x)$	$\hat{m}(x)$	$x_i : P(x_j < x_i) = P(x_j > x_i) = \frac{1}{2}; x_i \neq x_j$

### III. RESULTS AND INTERPRETATION

#### A. Participants and Data Acquisition

We tested 7 patients (2 m, 5 f) and 9 healthy human subjects (m: 6, f: 3). The patients' mean age was 60.57 ( $\pm 9.03$ ) years, the healthy subjects' mean age was 33.5 ( $\pm 10.6$ ) years. For the assessment of healthy subjects we scheduled testing sessions on three different days within 2 weeks. Patients' data were recorded over a period of three months. 3 patients suffered from right-sided posterior canalolithiasis; 1 patient suffered from left-sided posterior canalolithiasis; 1 patient suffered from bilateral posterior canalolithiasis; 1 patient suffered from left-sided posterior and horizontal canalolithiasis; 1 patient suffered from right-sided posterior canalolithiasis and horizontal cupulolithiasis. In two patients, the sensor system only recorded the data of the post-therapy tests for one foot correctly.

Every healthy subject was recorded once before and once after liberation maneuvers; one healthy subject was required to redo the test because the sensor system became non-operational due to low battery power. All patients, except for one, required only one liberation maneuver for successful treatment. One subject suffered from recurrence of BPPV symptoms and was liberated four times. In this patient, to avoid subject-caused bias, we included only data from the first therapy session in our analysis.

TABLE II  
COEFFICIENT OF VARIATION, CV.  $CV.x$  OR  $CV.y$  ARE THE CV VALUES OF THE X COORDINATE OR THE Y COORDINATE, RESP. LARGER VALUES ARE PRINTED IN BOLD. VALUES ARE PRESENTED AS (PRE-THERAPY / POST-THERAPY).

Test	CV.x	CV.y
R1, R2	0.143 / 0.182	<b>0.213 / 0.217</b>
T	<b>0.252 / 0.296</b>	0.190 / 0.192

Several subjects (patients and healthy) lost balance within the 20 seconds of the tandem tests, **T**. These events were visible in the accelerometer data and were manually removed such that only stable periods were included for further analysis. However, to avoid learning effects ([22]), we did not repeat the test in these situations.

#### B. Data Analysis

For tests **R1** and **R2** (Romberg) the major COP instabilities appeared mainly in the forward/backward direction (Y coordinate), while for **T** (tandem), the instabilities occurred in the left/right direction (X coordinate). We used the coefficient of variation, CV, ( $\sigma/\mu$ ) to estimate the instabilities. CV is a measure of the dispersion of a set of coordinates. Table II provides the results of an analysis on the data from healthy subjects. Analysis of data from patients created similar results. Thus, for tests **R1** and **R2** we further analyzed the *Y-dimension* of the pressure sensor (coordinate range 1-60) and for test **T** the *X-dimension* (range 1-20). In the tables below the features were calculated on *coordinates* of the pressure insole (see subsection II-C).

In the following we address our hypotheses and present the corresponding results.

The first hypothesis, **H1**, holds that patients and healthy subjects differ significantly in their balance performances prior to any therapy. The Romberg test is a well-known surrogate for bipedal standing performance. We compared patients and



(a) Romberg on foam, (R2)

(b) Tandem stance, (T)

Fig. 7. Two Romberg test items

TABLE III

STATISTICAL ANALYSIS OF **H1** FOR TESTS 1-3 *before* THE THERAPY. THE NUMBERS ABOVE ARE LISTED AS *healthy subject / patient* VALUES. SIGNIFICANT ( $p < 0.001$ ) DIFFERENCES ARE **bold**.

Test #	mean	variance	median
R1	<b>24.56 / 25.79</b>	2.481 / 3.219	<b>24.64 / 25.87</b>
R2	<b>25.33 / 25.93</b>	3.351 / 3.889	<b>25.41 / 25.99</b>
T	11.51 / 11.56	1.37 / 1.667	11.55 / 11.6

healthy subjects during the classical Romberg test (standing with feet together and eyes closed, **R1**) and its more difficult variations in which subjects are required to stand on a piece of foam (**R2**, see Figure 7a) or on even ground in tandem stance (**T**, see Figure 7b). Results of the statistical analysis of all features are listed in Table III. Note the different ranges of values (e.g. insole coordinates) between tests. As we explained above, for **R1** and **R2** the range of possible values was  $[1 - 60]$ , for test **T** the coordinates fell within the interval  $[1 - 20]$ . The tables list average values on COP coordinates for all tests **R1**, **R2**, **T** and features (cf. subsection II-C). In Table III, the first number represents data from healthy subjects, the second number represents data from patients. Each row contains data for a specific test, e.g. data for **R1** are in row 1.

**H1** could not be rejected statistically, i.e., there were significant differences of performance between healthy subjects and patients. The mean values and the median values of the COP were significantly lower in healthy subjects than in patients. Thus, healthy subjects kept their center-of-pressure (COP) closer to the heels than patients. The feature *variance* did not reveal significant difference between patients and healthy subjects. Interestingly, performance in **T**, the tandem-stance test, was similar in patients and in healthy subjects: there were no statistically significant differences between the two groups prior to therapy. Whether the small statistically significant differences for **R1** and **R2** are clinically relevant need to be addressed in subsequent studies.

Hypothesis **H2** could not be rejected statistically as well (see Table IV), i.e., the Epley maneuver affected the patient group.

TABLE IV

STATISTICAL ANALYSIS OF **H2** FOR TESTS 1-3 FOR *patients*. NUMBERS REPRESENT AS (*before / after*) MEANS. SIGNIFICANT ( $p < 0.001$ ) VALUES ARE **bold**.

Test #	mean	variance	median
R1	<b>25.79 / 27.21</b>	3.219 / 3.218	<b>25.87 / 27.28</b>
R2	<b>25.93 / 27.43</b>	3.889 / 3.888	<b>25.99 / 27.5</b>
T	11.56 / 11.69	1.667 / 1.858	11.6 / 11.74

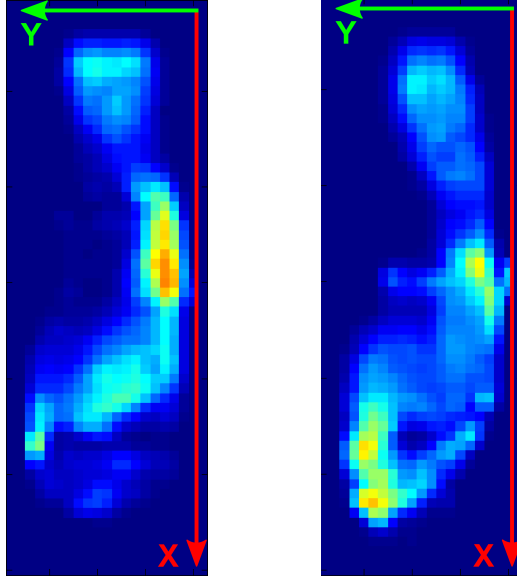
TABLE V

STATISTICAL ANALYSIS OF **H3** FOR TESTS 1-3 FOR *healthy subjects*. NUMBERS REPRESENT AS (*before / after*) MEANS. SIGNIFICANT ( $p < 0.001$ ) VALUES ARE **bold**.

Test #	mean	variance	median
R1	24.56 / 24.71	2.481 / 2.482	24.64 / 24.79
R2	<b>25.33 / 24.63</b>	3.351 / 3.350	<b>25.41 / 24.74</b>
T	<b>11.51 / 9.997</b>	<b>1.37 / 1.868</b>	<b>11.55 / 10.04</b>

Test performances after therapy were significantly different to performances assessed before the intervention. As a reaction to treatment, patients shifted the mean and median COP significantly closer to the toes. After therapy, mean COP values were approximately 1.5 coordinate counts ( $\approx 7.5mm$ ) closer to the toes in **R1** and **R2**. The median shifted similarly. Variance of COP was not affected significantly. Interestingly, there was no noticeable adaption of patients in the tandem test, **T**. Patients applied a different postural strategy after the Epley maneuver in **R1** and **R2** than after **T**.

Hypothesis **H3** holds that the therapy should not have statistically significant effects on healthy subjects. **H3** was rejected statistically (see Table V). For **R1**, healthy subjects showed no significant reaction to the Epley maneuver. However surprisingly, healthy subjects showed a statistically significant reaction to both **R2** and **T**. In **R2**, healthy subjects shifted the mean and median COP slightly towards the heels ( $\sim 0.7$  coordinates  $\approx 3mm$ ). Whether this small, but significant difference is clinically relevant, should be addressed in subsequent studies. A stronger reaction to the Epley maneuver was seen in tandem test **T**. Data suggested that healthy subjects tried to stabilize the tandem stance by shifting the mean and median COP towards the lateral side of their feet. On average the COP shifted about 1.5 coordinates ( $\approx 7.5mm$ ) towards the lateral side. Figure 8 visualizes typical examples during the tandem task. In Figure 8a, the mean pressure during **T** of a healthy subjects is shown, while in Figure 8b, mean data during **T** in a patient is depicted. The two images are representative for the statistical evidence presented above: after the Epley maneuver, for the tandem task, healthy subjects shift their COP to the lateral side of the feet; patients, however, did apply different strategy. As discussed above, both groups showed reactions to the Epley maneuver, but both had different compensation mechanisms. Healthy subjects shifted their COP in the backward direction, while patients shifted it forward towards the toes. Further, the range of COP coordinates (range =  $[min, max]$ ; see Table VI) in healthy subjects changed not significantly after the Epley maneuver whereas in patients the sway increased significantly for both tests. Overall, patients



(a) Mean force during tandem stance of a healthy subject. (b) Mean force during tandem stance of a patient.

Fig. 8. Comparing stabilization strategies of a healthy subject (left) and a patient after the Epley maneuver. As analysis revealed healthy subjects shift the mean COP towards the lateral arch of their feet while patients fail to do so.

TABLE VI

CHANGES IN *range* OF COP DATA IN HEALTHY (SUBSCRIPT H) AND PATIENTS (SUBSCRIPT P). FOR THE TESTS R1 AND R2 COP Y-COORDINATES WERE ANALYZED. ALL DIFFERENCES IN THE PATIENTS GROUP WERE STATISTICALLY SIGNIFICANT WITH ( $p < 0.05$ ). VALUES ARE PRESENTED AS PRE- / POST- THERAPY.

Test	Range <sub>H</sub>	Range <sub>P</sub>
R1	8.111 / 8.778	<b>11.778 / 13.444</b>
R2	11.250 / 10.875	<b>14.625 / 16.000</b>

showed a stronger reaction to the therapy than healthy subjects.

We trained supervised and unsupervised classifiers on patient and healthy-subject data. The task was to discriminate between before-therapy and after-therapy performance for each group. Table VII shows the performance of the classifiers on healthy

TABLE VII

CLASSIFIER PERFORMANCES ON HEALTHY SUBJECTS' DATA. RESULTS OF THE BEST CLASSIFIER ARE **bold**.

Test #	SVM	kNN	Naive Bayes	GMM	k-Means
R1	<b>89.8012</b>	81.2716	61.973	48.1417	51.3984
R2	79.0258	<b>80.0398</b>	59.7217	51.0934	50.9294
T	83.4409	<b>87.4946</b>	62.9351	47.6344	50.1882

TABLE VIII

CLASSIFIER PERFORMANCES ON PATIENTS' DATA. RESULTS OF THE BEST CLASSIFIER ARE **bold**.

Test #	SVM	kNN	Naive Bayes	GMM	k-Means
R1	91.7247	<b>91.835</b>	78.5864	51.3066	50.4843
R2	86.4986	<b>87.2076</b>	73.2638	50.7651	51.1206
T	78.0059	<b>88.0227</b>	65.6311	48.4848	51.2512

TABLE IX

CLASSIFICATION PERFORMANCE FOR DIFFERENT CLASSIFIERS ON **H3**. RESULT OF THE BEST CLASSIFIER FOR EACH TEST (1-3) IS HIGHLIGHTED WITH **bold** FONT.

Test #	SVM	kNN	Naive Bayes	GMM	k-Means
R1	<b>86.3833</b>	86.1256	51.0232	46.6609	50.3981
R2	75.4253	<b>76.8984</b>	63.3925	52.6465	49.3667
T	68.5773	<b>78.6738</b>	65.8821	50.4606	52.1894

subject data. For **R1** SVM showed the best performance with 89% correct classification. For **R2** and **T** the kNN classifier outperformed all other classifiers. On the data of patients, kNN outperformed all other classifiers with an average correct classification rate of 88%. Table VIII shows the results.

We formulated another classification tasks: we aimed to investigate the performance of the best classifier to separate healthy subjects from patients. Data of before and after the therapy for both groups were used by the algorithms. Table IX shows the results of the classifiers. For **R1**, SVM performed slightly better than the other classifiers. However, for **R2** and **T** kNN showed a better performance. With a mean accuracy of approximately 80% kNN outperformed the other classifiers.

### C. Other Findings

Analysis of the time stamps during the walking task did not reveal any significant differences between healthy subjects and patients. This did not match our expectations since imbalance *could* result in changes of walking speed ([23], [24]). We assume, however, that the discrepancy between these data and our expectations maybe caused by the way we assessed walking speed. In order to be able to prevent a subject from falling, one of the authors (R.A.) was walking close to the subjects. We believe that the subjects subconsciously adapted their walking speed to match the speed of the experimenter, even though we asked them to walk at a fast, but freely chosen speed. We will address this in future studies.

## IV. CONCLUSION AND OUTLOOK

In this work we, introduced a system for automated Romberg testing and demonstrated its feasibility with an investigation on the effects of a treatment for Benign Paroxysmal Positional Vertigo (BPPV). In prior work, it has been reported that patients suffered a temporary exacerbation of their subjective postural imbalance following an Epley maneuver [17], [25], [26]. So far, this effect was not further investigated. In this work, we investigated three hypotheses. We could not reject statistically the first hypothesis, **H1**: patients with BPPV and healthy subjects differ significantly in their bipedal performance. We also could not reject statistically **H2**: the Epley maneuver provoked a measurable and statistically significant change of bipedal-performance features in patients. However,



we could reject **H3** statistically: the Epley maneuver also had a statistically significant effect on bipedal performance in healthy people. We used a sensor system measuring inertial data and force applied to the feet in order to assess the bipedal performance of the subjects. We recorded data from 7 patients and 9 healthy subjects. Inertial data and force data were statistically analyzed and classifiers were trained.

Patients differed significantly from healthy subjects, i.e. the impact of BPPV was measurable. The Epley maneuver affected the bipedal performance of patients. However, there was, unexpectedly, a statistically significant difference between the performance of healthy subjects before and after the Epley maneuver. The control subjects adapted a different stabilization strategy than patients, however.

One limitation of this study was the significant age difference between patients and control subjects. The age differences could have introduced differences in pre-treatment postural values and differences in response to liberation maneuvers.

Based on our findings, we plan future studies addressing these effects. As we introduced in the motivation it could be helpful if the severity of BPPV, the efficacy of the treatment and other therapy related parameters could be estimated by an automated system. Such a system possibly could assist as a diagnosis tool for better matching a therapy schedule to individual needs of individual patients. The duration of treatment could be reduced and the overall efficacy of treatments could be increased.

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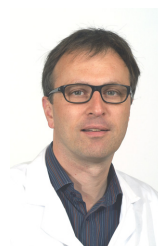


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